



The MSL SkyCrane Landing Architecture A GN&C Perspective

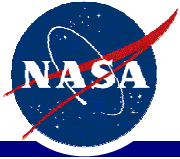
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International Planetary Probe Conference

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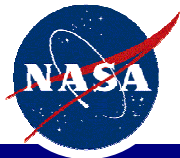


A Few Definitions



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- The Delivery System/Phase
 - Starts during the Parachute Descent phase and ends at first ground contact
- The Touchdown System/Phase
 - Starts at first ground contact and ends at 6-DOF full stop
- The Safing/Egress System/Phase
 - Starts at full stop and ends when the payload is power, thermal, and telecom safe and ready to start the science commissioning phase



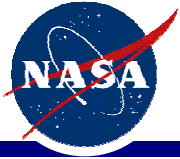
Terminal Descent Architectures

The Role of GN&C



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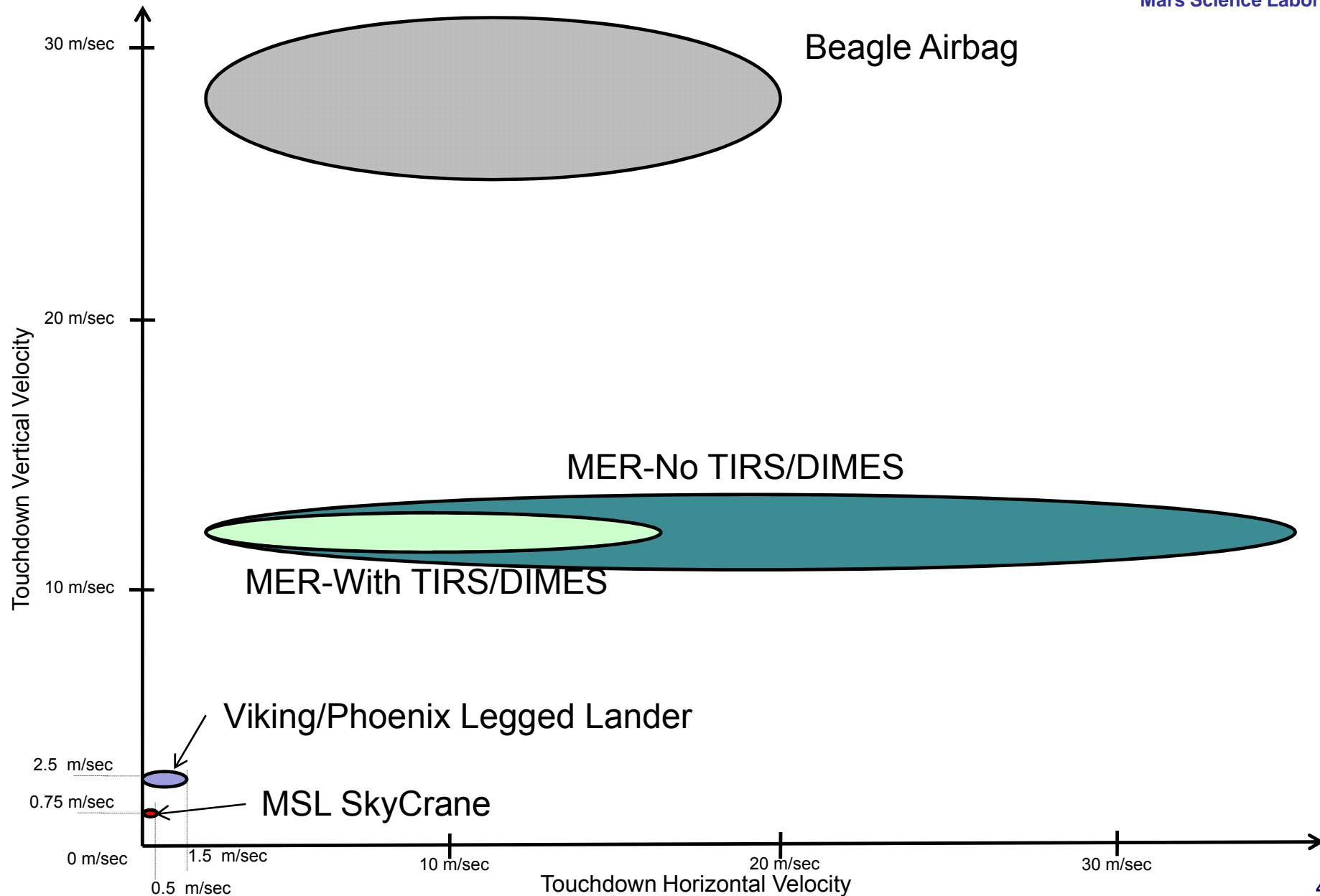
	Beagle Airbag	MPF/MER Airbag	Legged Lander	Sky-Crane
Delivery System/Phase	<ul style="list-style-type: none"> • Subsonic Chute • Altimeter (for airbag inflation) 	<ul style="list-style-type: none"> • Altimeter • RAD Rockets • IMU-TIRS/DIMES 	<ul style="list-style-type: none"> • Altimeter/Velocimeter • IMU • Thrusters • Leg Deploy 	<ul style="list-style-type: none"> • Altimeter/Velocimeter • IMU • Thrusters • Mobility Deploy
Touchdown System/Phase	<ul style="list-style-type: none"> • Airbags • Shock Absorbing Structure 	<ul style="list-style-type: none"> • Airbag 	<ul style="list-style-type: none"> • Shock Absorbing Legs • Touchdown Detection sensors 	<ul style="list-style-type: none"> • Altimeter/Velocimeter • IMU • Thrusters • Mobility System
Egress-Safing System/Phase	<ul style="list-style-type: none"> • Petal Actuation 	<ul style="list-style-type: none"> • Airbag-Retraction • Petal Actuation • Rover Stand-Up ... • Rover Egress-Aids 	<ul style="list-style-type: none"> • Ramps • Cranes 	<ul style="list-style-type: none"> • None

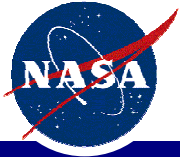


Delivery System TD Velocity Performance



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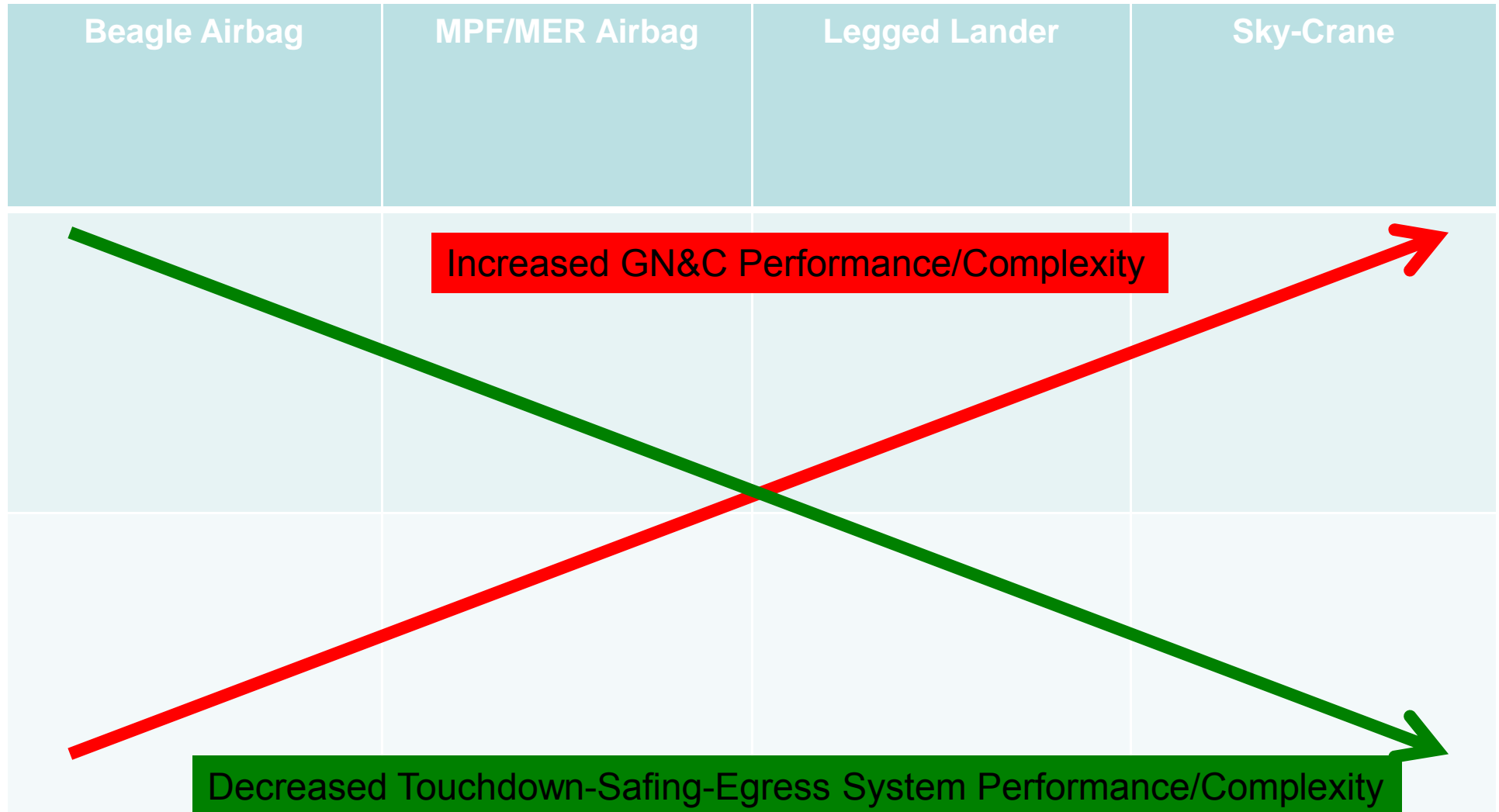


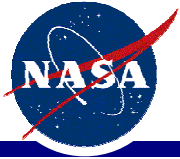


Terminal Descent Architectures



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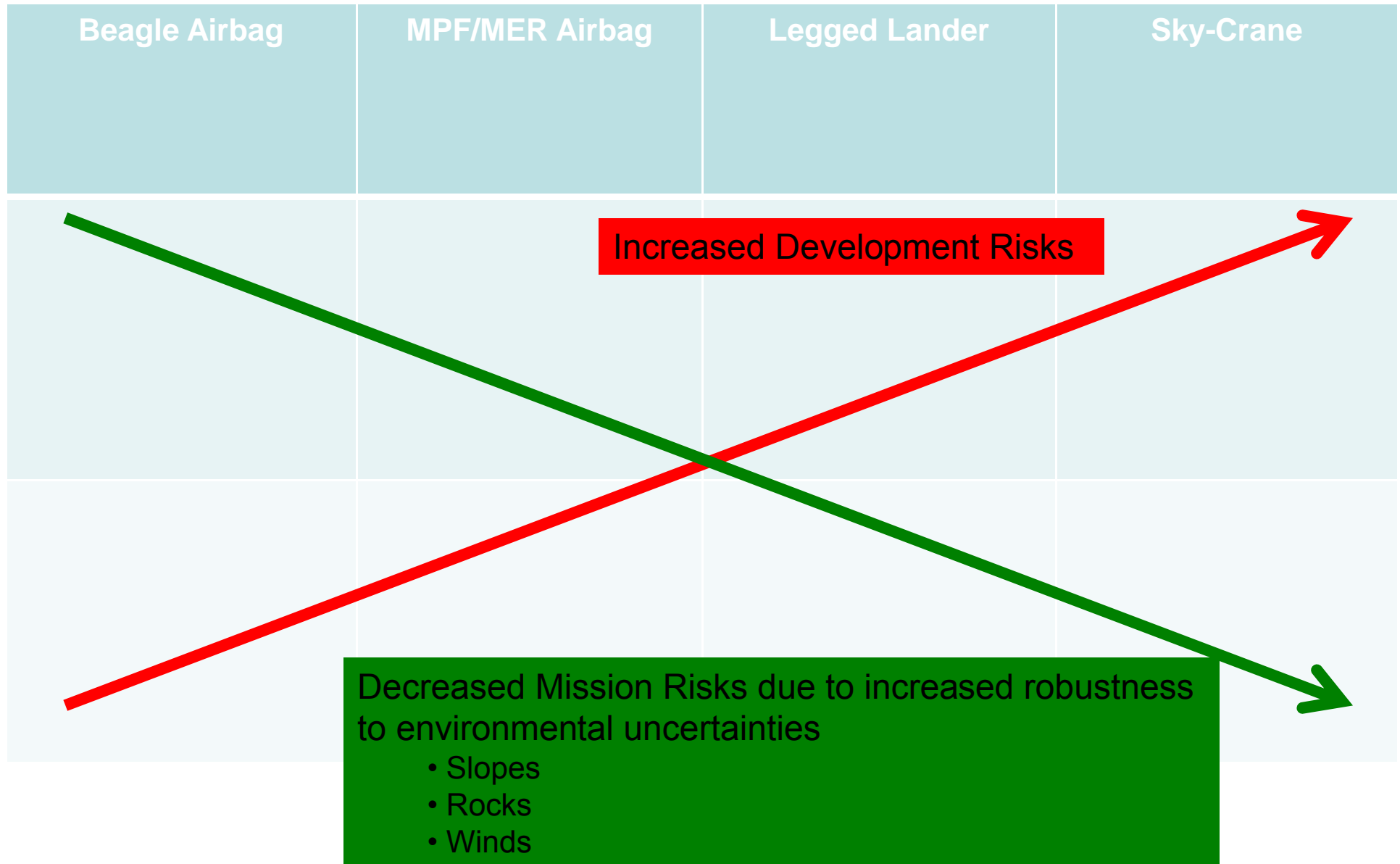


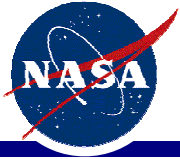


Terminal Descent Architectures



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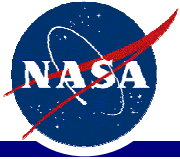


Load and Stability Limitations of Viking Type Landers at Touchdown



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- Ground thruster plume interaction requires large vertical approach speeds to deal with:
 - Trenching effects
 - Dust effects
 - Ground pressure effects
- Due to the coupling between translational and attitude control (and vice versa) GN&C/thrusting must stop immediately at first contact with the ground
 - Improves lander stability (let the g-vector stabilize the landing)
 - Requires touchdown sensors
 - Millisecond sensor response
 - On slopes the lander will drop resulting in increased loads
- **The combination of these two effects impedes further reduction of touchdown velocities and resulting loads resulting in:**
 - **The need for more capable shock absorbing legs**
 - **Lower touchdown stability in the presence of slopes and rocks**
 - **Stricter landing site selection requirements**
 - **Active Hazard Detection and Avoidance**

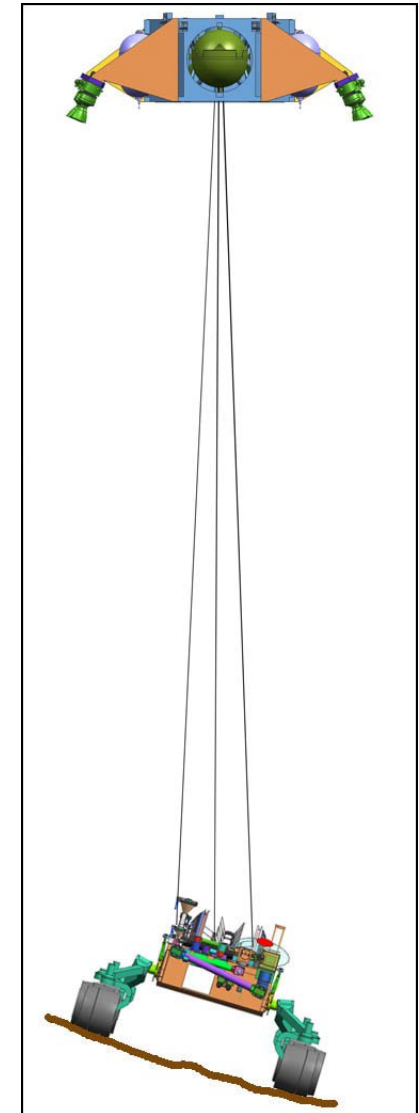


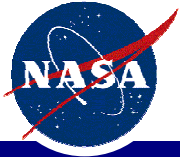
Advantages of the SkyCrane at Touchdown



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- Two-body architecture and rocket plumes distance to the ground enables continued GN&C operation during touchdown event
- **GN&C is part of the Touchdown System**
- The Descent Stage softly offloads the rover on the Mars surface
 - Reduces touchdown loads
 - Improves touchdown stability
 - Can land on mobility
 - No need for specialized touchdown gear
 - Solves rover egress problem
- Minimum touchdown vertical velocity is limited by fuel
 - Driven by altitude knowledge errors

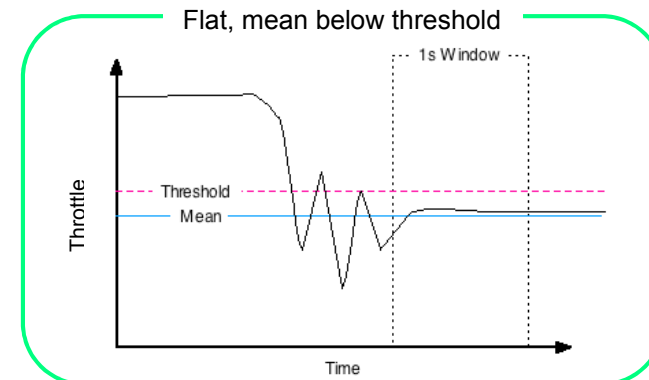
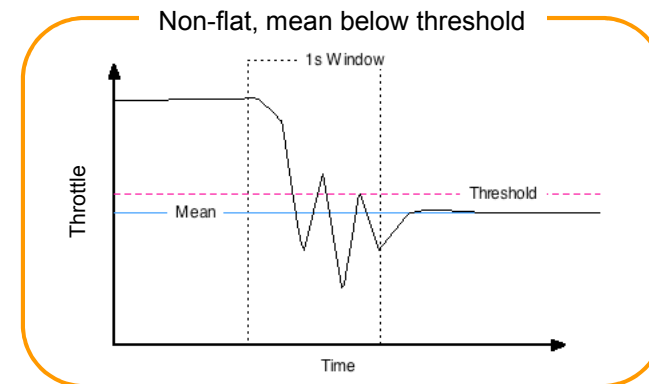
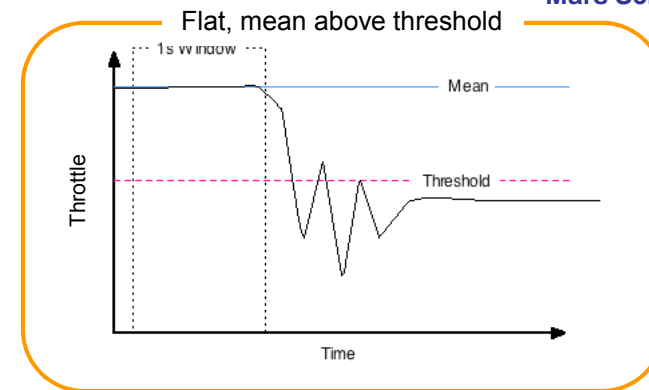
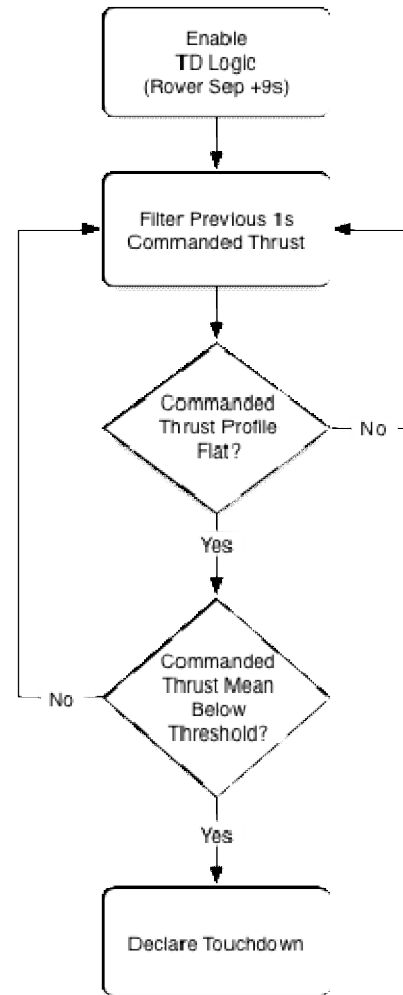
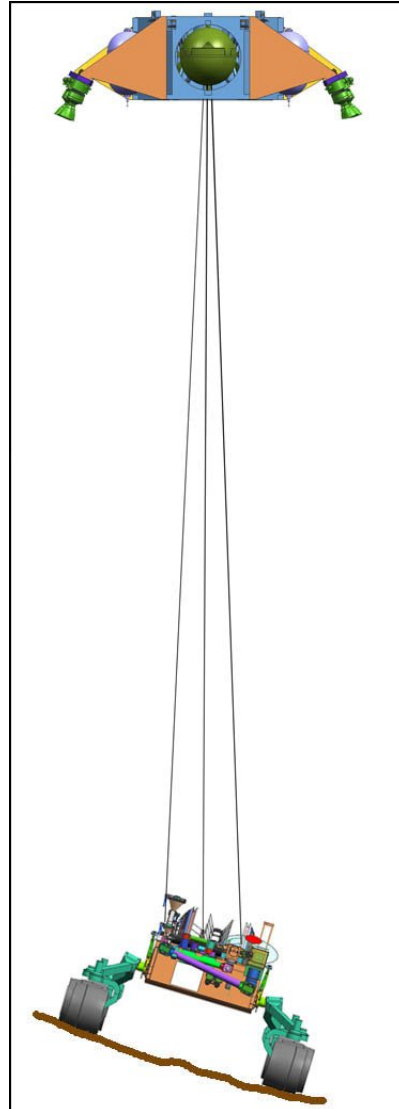


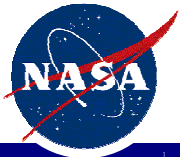


SkyCrane Touchdown Detection



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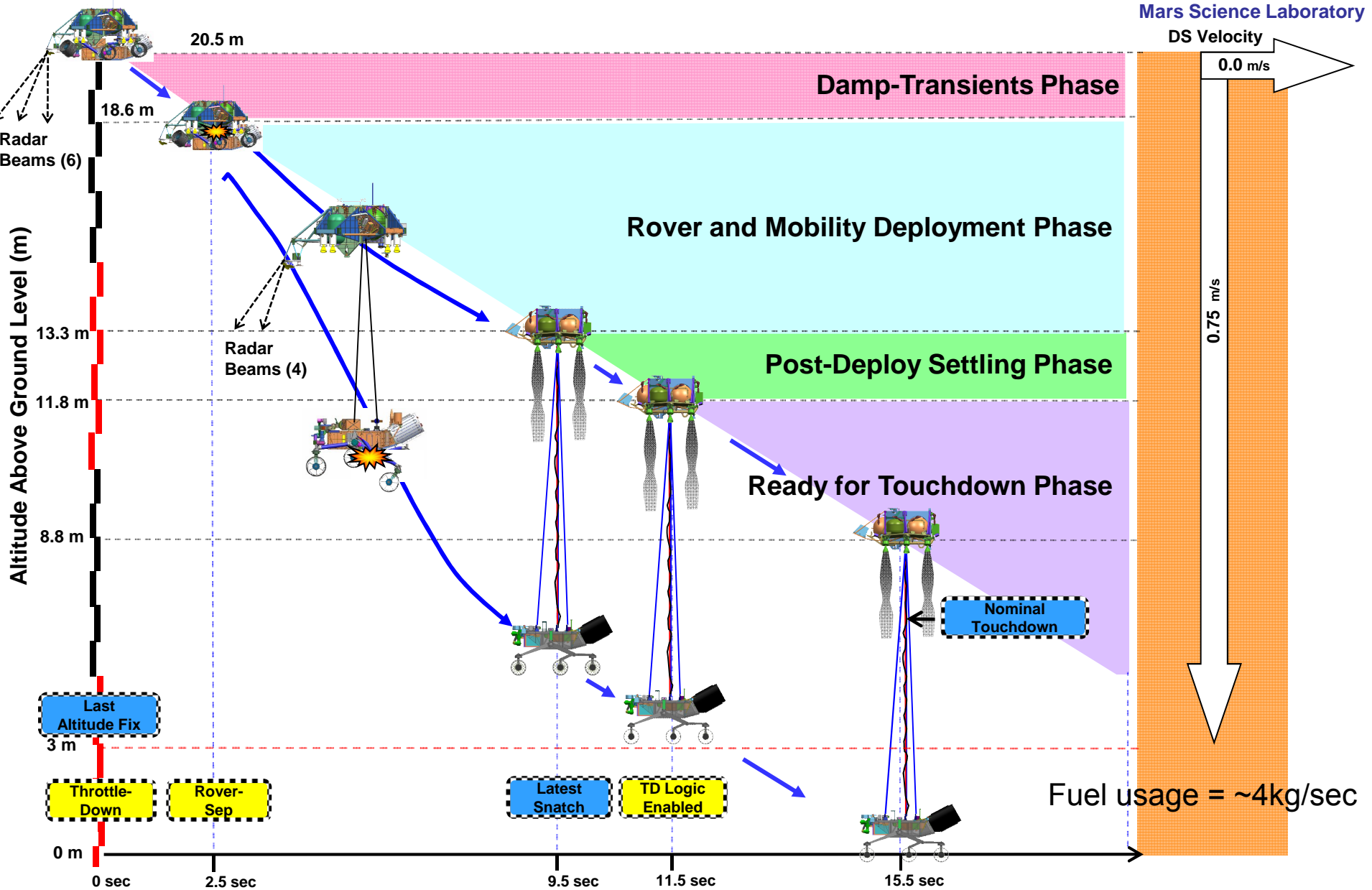




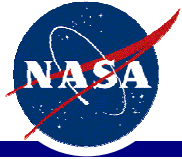
Sky Crane Maneuver Description



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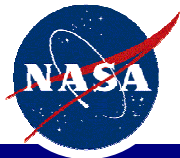


The Sky-Crane GN&C Problem Definition



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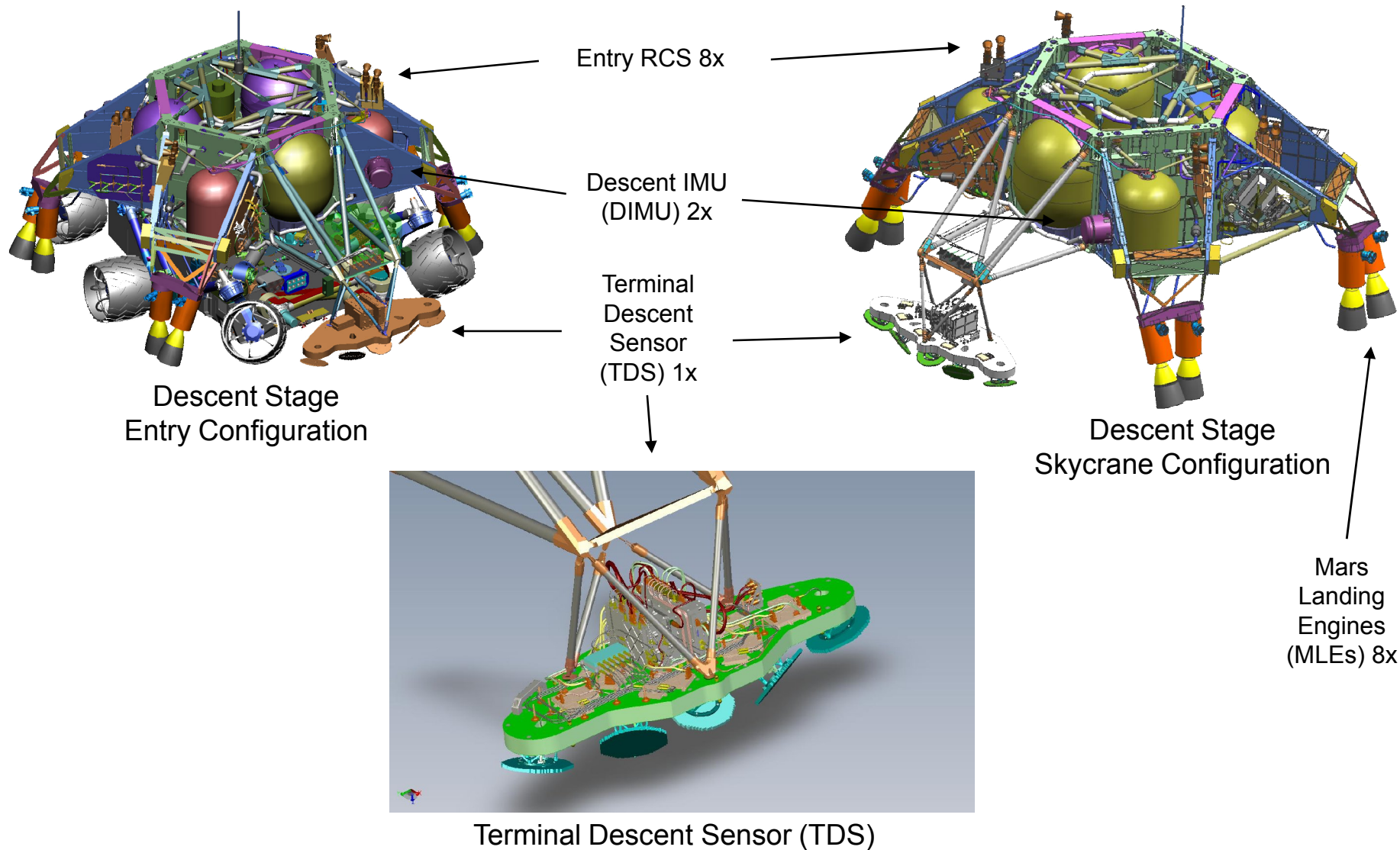
- *Avoid Re-Contact* => Rover Separation Requirements
 - Off-nadir attitude error < 3 deg (3-sigma)
 - Attitude rate < 3 deg/sec (3-sigma)
- *Rover Loads & Stability* => Rover Touchdown Velocity Requirements
 - Vertical velocity = 0.75 m/sec, +/- 0.1m/sec (3-sigma)
 - Horizontal velocity < 0.5 m/sec (3-sigma)
- *Avoid Rover Pluming* => Descent-Stage Touchdown Requirements
 - Horizontal velocity < 0.1 m/sec (3-sigma)
- Disturbances
 - Throttle Down
 - CG Offset, MLE thrust errors
 - Rover Separation
 - CG Offsets, Rover off-load
 - Rover Deployment snatch
 - Touchdown
 - Half of the weight off!
- Fuel consumption rate = ~4kg/sec => **Time is of the essence!!**

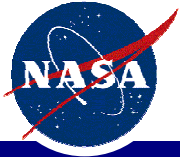


Descent Stage Configuration



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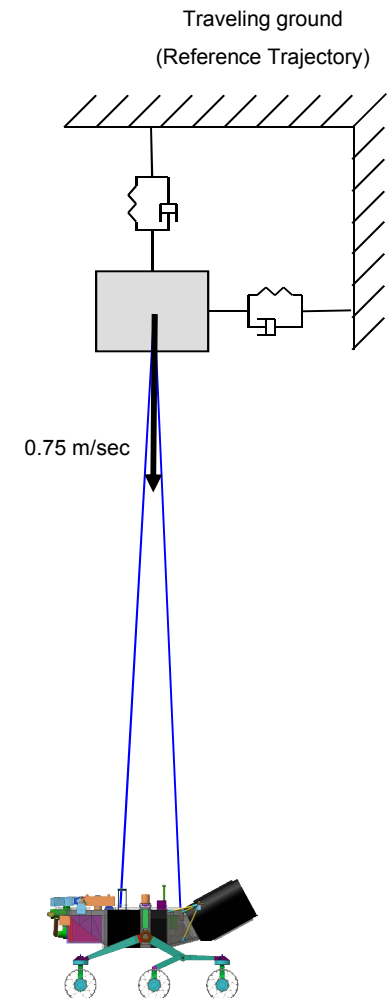


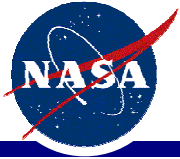
Control Law Architecture



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- Descent Stage Reference Trajectory
 - Horizontal velocity = 0 m/sec
 - Vertical velocity = 0.75 m/sec
 - Attitude = z-axis aligned with local vertical
 - *Note: This Reference Trajectory applies to the full Sky Crane Phase including the full duration of the touchdown event (i.e. until the full rover weight has been transferred to the ground, as detected by the Touchdown Logic)*
- The purpose of the Position and Attitude control loops is to follow the Reference Trajectory position and velocity as close as possible in the presence of disturbances
 - Throttle down (of MLE's) at start of Sky Crane maneuver
 - Rover deploy, Mobility deploy, and bridle snatch
 - Wind, Slosh, others
 - Touchdown event



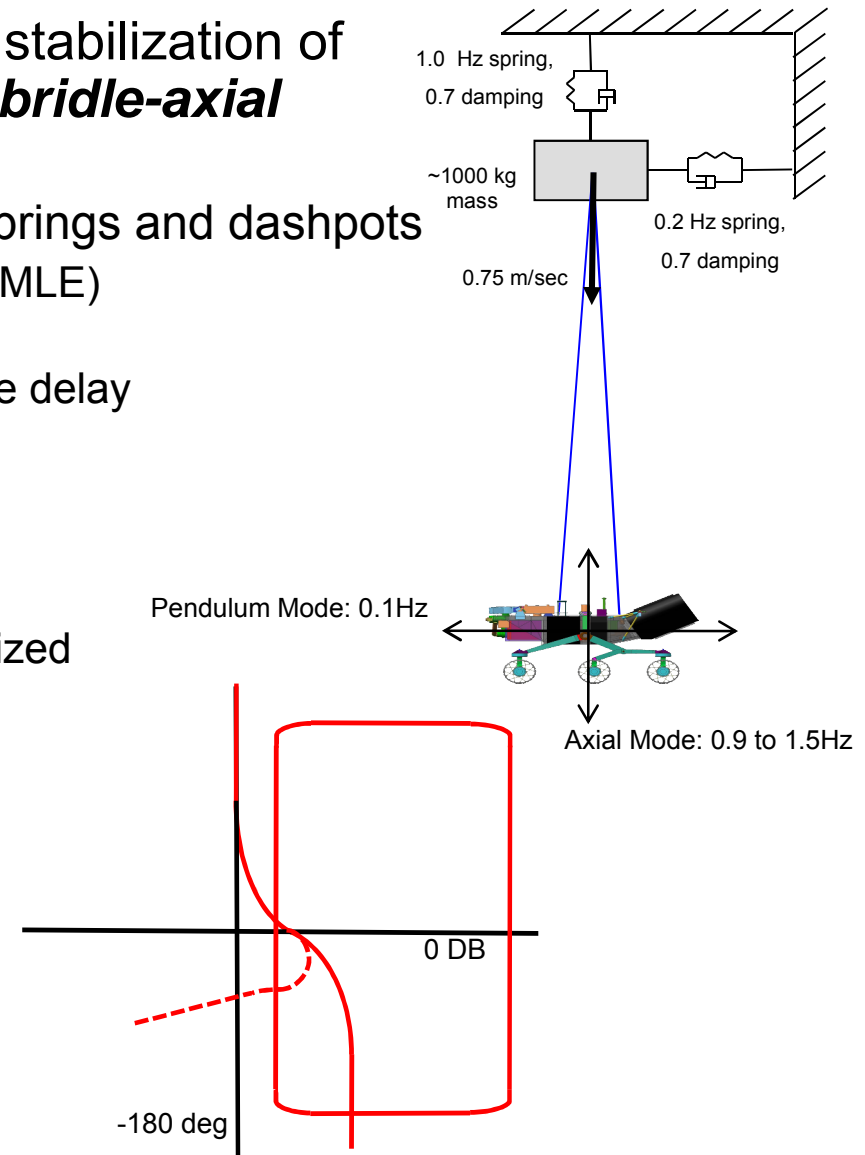


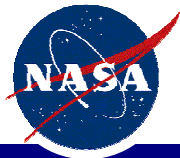
Control Design Design for Robustness



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- Robust stability is achieved by phase stabilization of **appendage modes (pendulum and bridle-axial modes)**
 - Make the control system behave as springs and dashpots
 - Collocated sensing (IMU) and control (MLE)
 - 16 Hz structure
 - High sampling rate and a single sample delay
 - 64 Hz sample rate
 - High bandwidth sensing and control
 - IMU bandwidth > 30 Hz
 - MLE bandwidth > 15 Hz
 - All modes below 5 Hz are phase stabilized
 - Fuel slosh modes < 2 Hz
 - Bridle mode axial 0.4 to 1 Hz
 - Pendulum mode < 0.2 Hz
 - System robust to uncertainty in mode
 - » Frequency
 - » Damping
 - Structural modes are gain-stabilized
 - 8th order roll-off filter

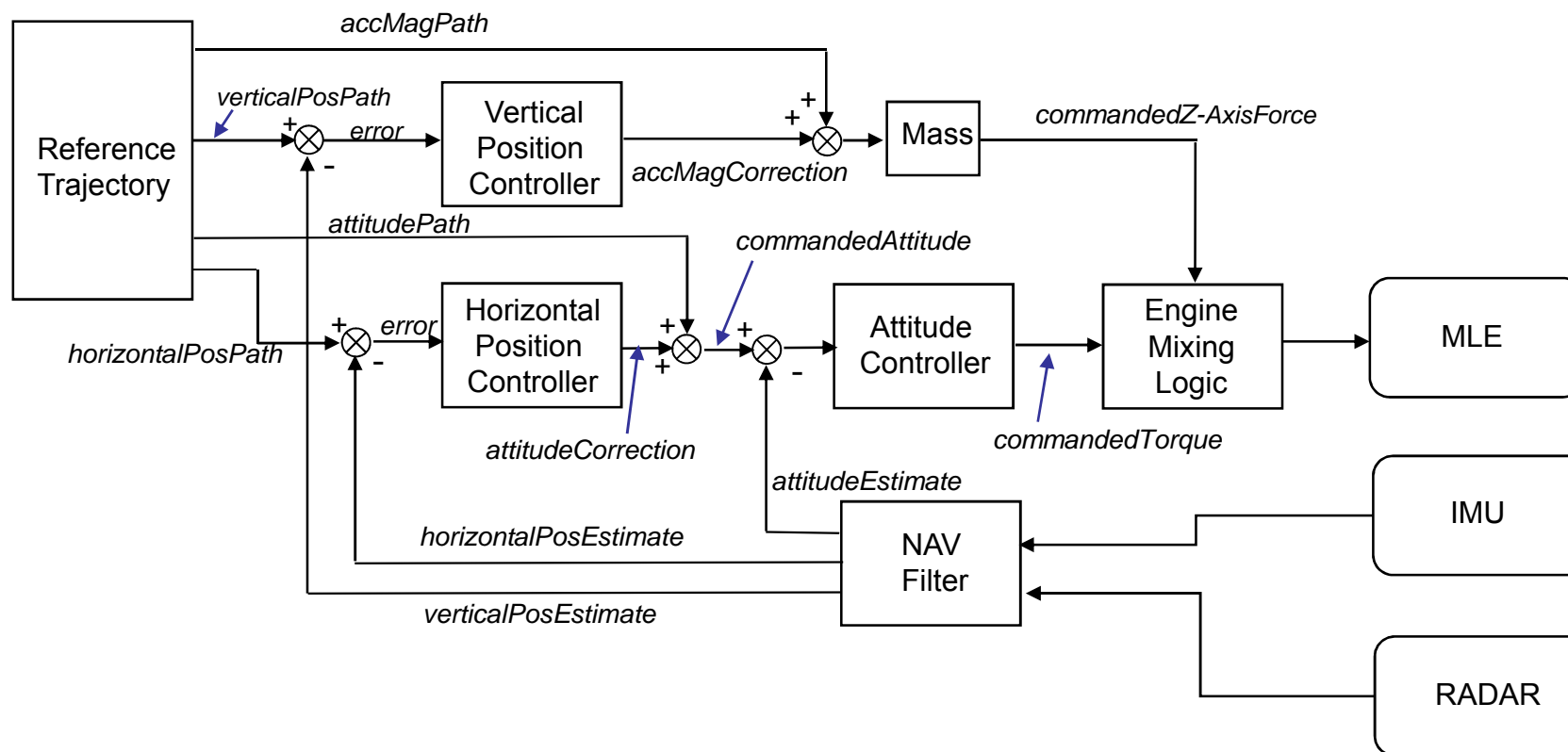


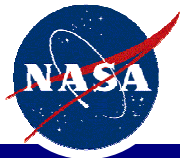


Control Block Diagram Sky Crane Phase



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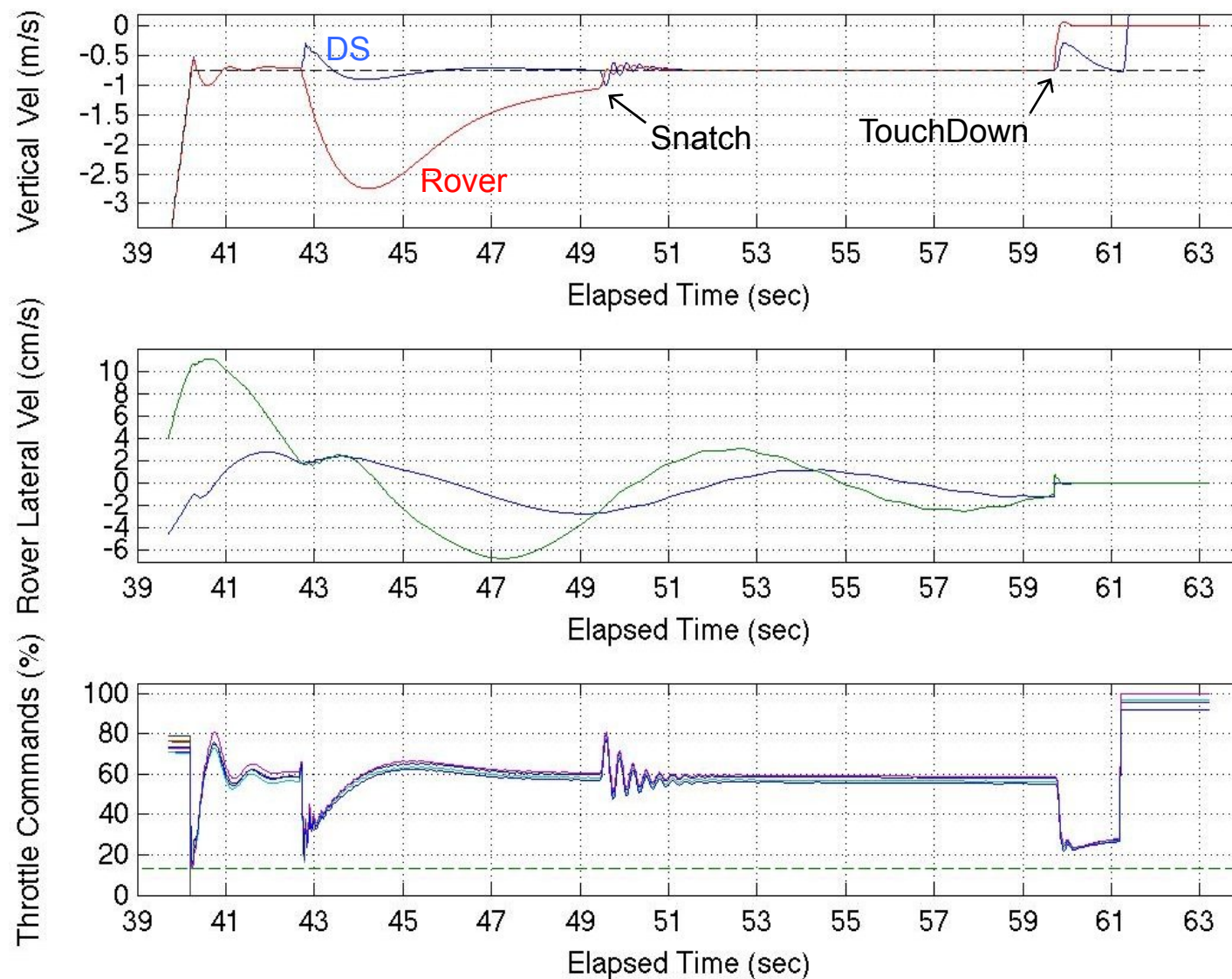


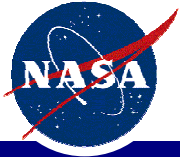
Simulations: Sky-Crane Behavior



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40.20 Throttle-Down
42.69 Rover Separation
49.43 Deployment Done
59.70 Touchdown
61.22 Fly-Away Start





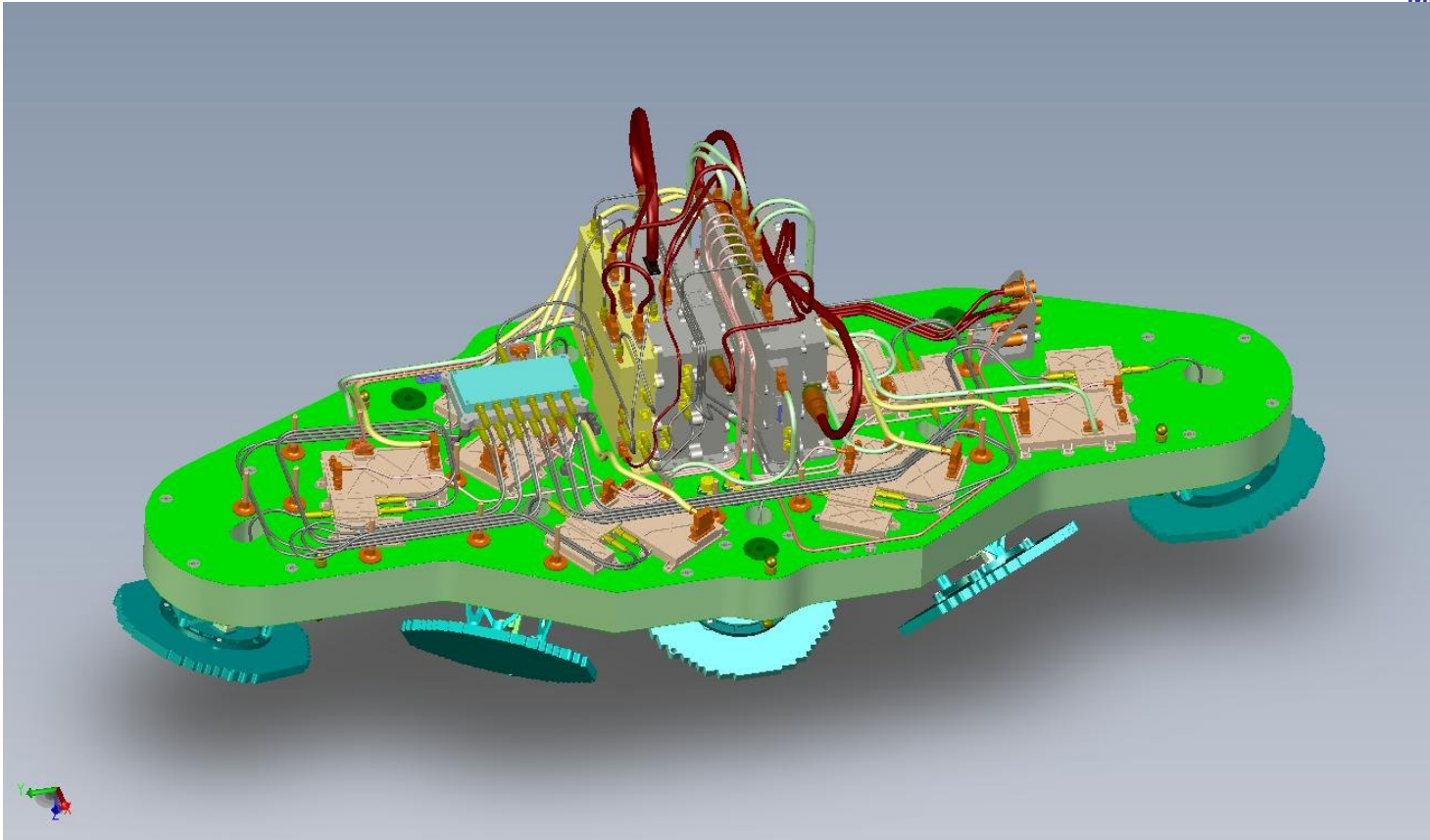
Terminal Descent Sensor



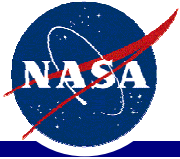
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- The low touchdown velocities requirements dictates the Terminal Descent Sensor (TDS) to be capable of measuring terrain relative velocity with high precision even in the presence of uncertain terrain slopes
- To satisfy this requirement, MSL has:
 - Specified a narrow beam, Doppler TDS sensor that measures terrain relative S/C velocity in the S/C reference frame
 - This makes the sensor highly insensitive to terrain slopes
 - Placed the TDS in the Descent Stage and configured the beams to allow continued velocity measurements through touchdown
 - Specified a vertical Sky Crane trajectory in combination with vertical beam that minimizes the effect of terrain on altitude measurement error

Terminal Descent Sensor



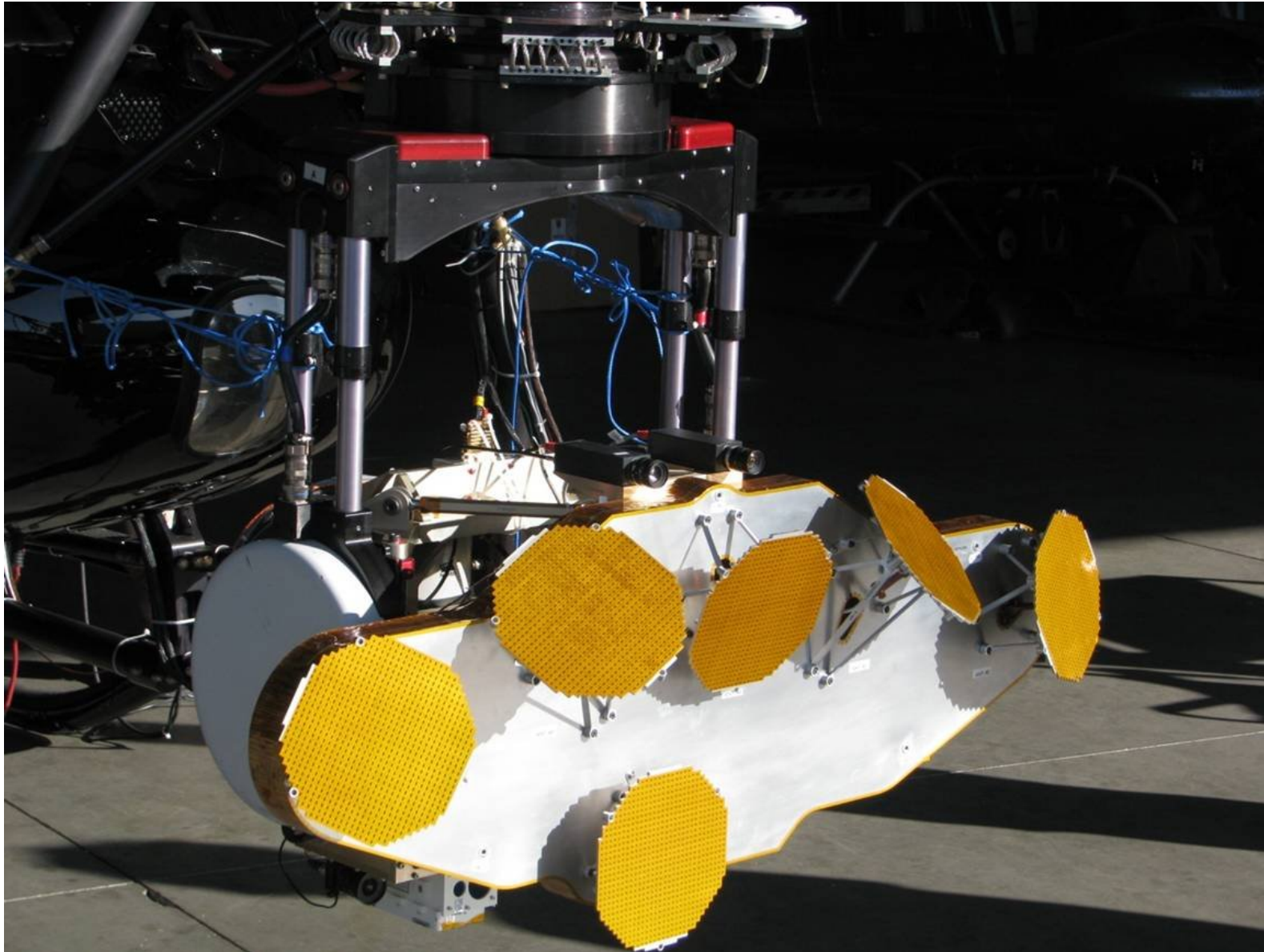
- **The Radar Terminal Descent Sensor produces line of sight range and velocity measurements on 6 independent beams**
 - Single antenna per beam, with 3 beams canted 20° off nadir, 2 beams canted 50° off nadir, and 1 nadir beam
 - Ka-band (35.75 GHz) center frequency
 - Pulse doppler radar design

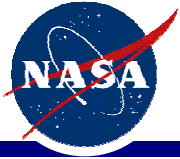


TDS



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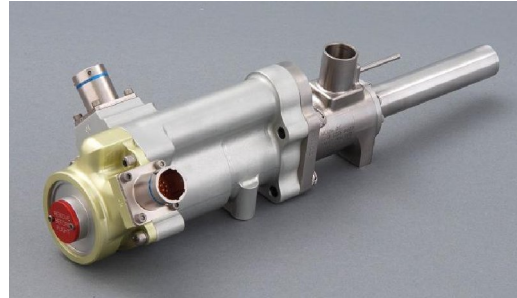
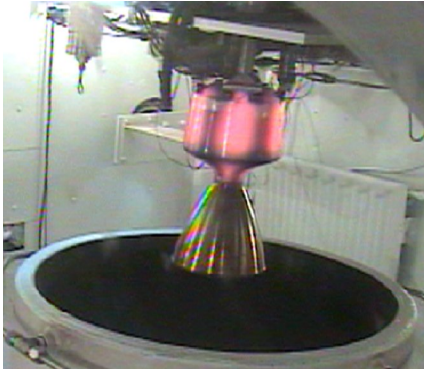




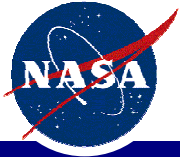
Key MLE Features



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- MLE design based on Viking descent thruster design
 - Updated catalyst bed retention design and updated materials
 - New cavitating Throttle Valve Assembly (TVA) makes flow independent of downstream pressure drop
- Key performance characteristics
 - Delivered thrust at maximum throttle setting ≥ 3060 N / engine at 600 psia inlet pressure
 - Nominal throttle range 400 N to 3060 N
 - Minimum specific impulse is a function of thrust level:
 - 221 lbf-s/lbm @ 3060 N
 - 213 lbf-s/lbm @ 1500 N
 - MLEs are capable of operating at “near shutdown” (about 1% of maximum flow):
 - Following initial ignition (prior to warm up)
 - From the start of the sky crane phase to the end of flyaway
 - There is no fully closed position of the throttle valve
- Bandwidth (TVA + reactor) = ~ 15 Hz
- Accuracy = 5%

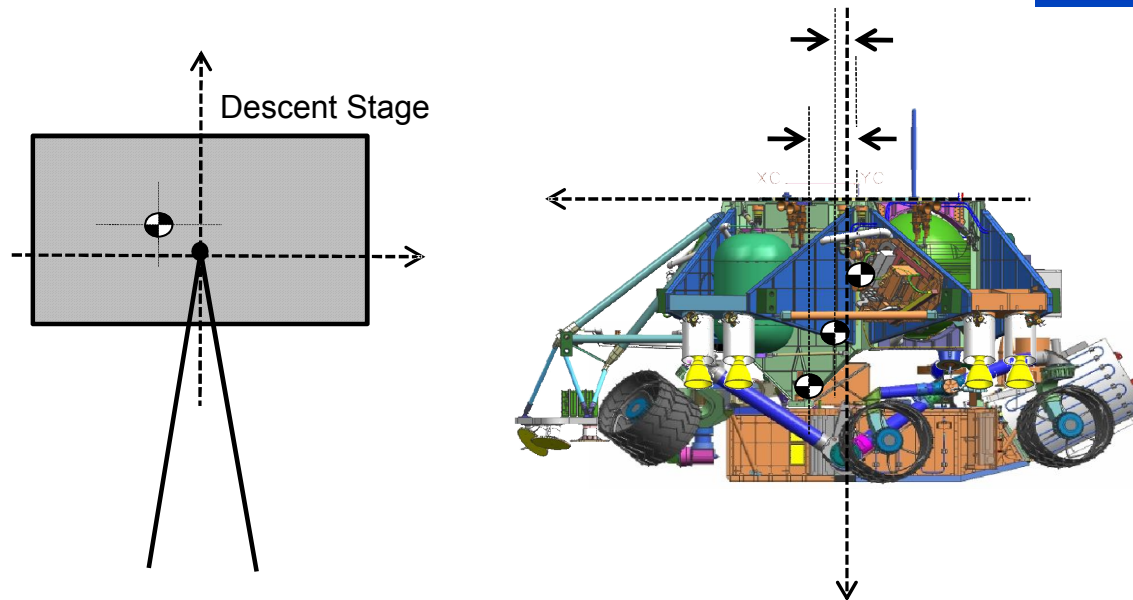
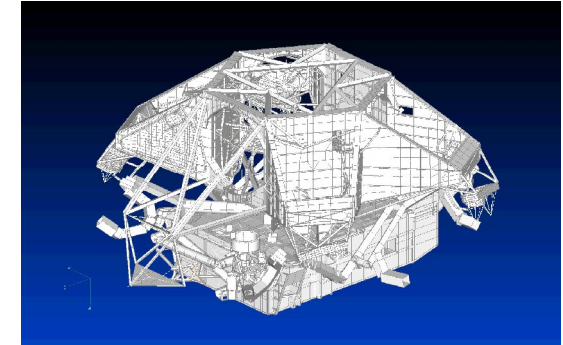


Requirements on Mechanical

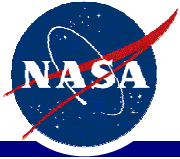


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- Structure Flexibility Requirements
 - First Mode $> 20\text{Hz}$
- Bridle Stiffness Requirement
 - Free-free axial mode = from 0.9 to 1.5 Hz
- Confluence Point & CG Offsets Requirements



- Sensor/Thruster Placement and FOV Requirements

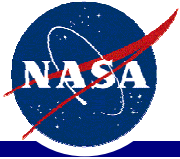


Fly Away



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- Descent Stage shall land at a distance > 100 meters from Rover
- Profiled-Closed-Loop pitch-rate profile
- Control law hosted in the Descent Stage MLE/TVA Motor Controller
 - Has access to MLE control
 - Added interface to IMU. Acts as a relay to the Rover Computer
- No explicit transfer of state data
 - Fly-away controller assumes that the Descent State state is
 - Zero velocity
 - Zero attitude rate
 - Aligned with vertical



Summary



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- The SkyCrane landing architecture enables low velocity touchdown on the rover wheels
 - Simplifies Touchdown and Egress Systems
 - Reduces Mission Risks by making the system more robust to terrain
- GN&C plays a major role in reducing the velocity prior and during the touchdown event
 - GN&C is part of the Touchdown System
- No additional hardware required to sense touchdown
- Two-Body pendulum and bridle-flex modes are phase-stabilized
- Structural modes are gain-stabilized
- High bandwidth control for high disturbance rejection and fast transient response during major events
 - Throttle-down
 - Rover-Sep
 - Touchdown